

An 8–14 Micron Infrared Astronomical Photometer

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A system for measurement of 8–14 μ infrared emission from extra-terrestrial objects is described. The photometric system utilizes a mercury-doped germanium detector cooled to liquid hydrogen temperature to achieve increased sensitivity in this spectral region. A method is presented for minimizing the problem of atmospheric and component emission. The system has been used to measure the radiation from the star α Orionis, from the unilluminated moon, and from several planets.

Introduction

Since gaseous constituents of the earth's atmosphere absorb strongly at a number of wavelength intervals throughout the electromagnetic spectrum, measurements of the radiation emitted by extra-terrestrial objects performed at the surface of the earth must necessarily be confined to those spectral regions known as atmospheric "windows." Conventional astronomy has been conducted largely in the visible "window" with extensions by photoelectric photometry into the edges of the ultraviolet and near infrared regions. Fairly recently techniques permitting greater utilization of the 3–5 μ atmospheric window have become available and work is progressing in this area.¹ With the exception of work by Sinton *et al.*,² however, only limited efforts have been made in recent years toward improving the measurements in the 8–14 μ window, due to the lack of sensitive detectors and to the severe restrictions imposed by environmental emission.

Further knowledge of the amount of radiation in the 8–14 μ interval emitted by the moon, planets, and stars is of special interest to astronomers. For the colder objects such as the darkened moon and the more distant planets this spectral region represents the only interval in which significant quantities of radiation are emitted. For the warmer planets and for stellar sources, this information, coupled with measurements at shorter wavelengths, provides further clues concerning the nature of planetary and stellar atmospheres.

At wavelengths shorter than about 5 μ the earth's atmosphere acts only as an absorbing and scattering medium which serves to reduce the energy available from an external source. However, as one approaches the 8–14 μ interval, emission by the atmospheric constituents becomes increasingly important. The emission spectrum of atmospheric gases has been studied by Goody³ and by Bell *et al.*⁴ Figure 1 shows the 8–14 μ sky radiance at various elevation angles as measured at Mt. Wilson. The total energy radiated in the 8–14 μ window is sufficient to produce a sky radiance many times that of the fainter external source to be measured. In addition, the telescope and photometer components within the field of view are even more intense sources of radiation. Essentially, the problem of photometry in this spectral region is equivalent to that which would be encountered in conducting stellar measurements in the visible region against a daytime sky while using a telescope constructed from luminescent materials.

Figure 2 shows the spectral transmittance in the 8–13 μ interval of the earth's atmosphere, obtained by Sinton and Strong⁵ at Palomar by square-root law extrapolation of data from several elevation angles. The strong absorption defining the edges of the atmospheric window is due to water vapor and, to a lesser extent, carbon dioxide. Since the concentrations of both of these atmospheric constituents are strongly dependent on elevation, transmittance and radiance are strongly altitude-dependent.

This paper discusses the techniques used in the construction and operation of an 8–14 μ infrared telescope utilizing quantum detectors recently developed⁶ for this spectral region rather than the conventional, less sensitive thermal detectors. The increased responsivity of these detectors, the use of special interference filters and cooled optical baffles, and operation

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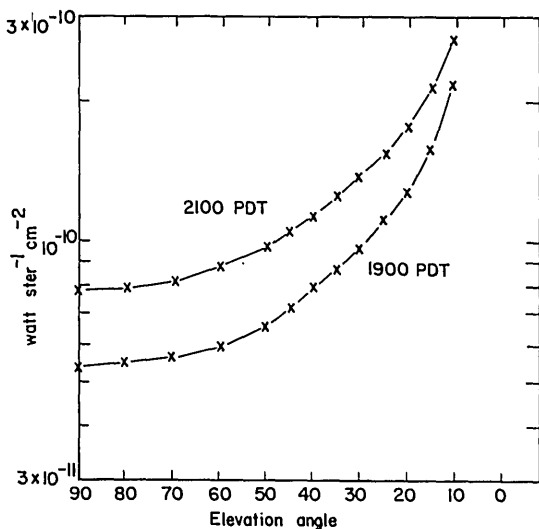


Fig. 1. The spectral radiation of a clear sky for several angles of elevation above the horizon, measured at Mt. Wilson, California, September 20, 1962.

of the system at a high altitude observing site have resulted in a significant increase in over-all signal-to-noise ratio. Details of measurements obtained at a White Mountain, California, site during the summer of 1962 will be reported in another paper now in preparation.

Telescope and Photometer

Since the peak emission from objects at room temperature occurs at about 9.6μ , it is necessary that the amount of extraneous background radiation on the cell be reduced to a minimum. The total power radiated in the $8\text{--}14 \mu$ interval from low-emissivity components such as mirrors, lenses, and windows is significant, and a careful choice of materials for the optical system is of importance. The emissivity of evaporated gold is the lowest ($\sim 1\%$ at 10μ) of any common metal⁷ and has been used on all mirrors in the system. Only one window, that on the cell dewar, was employed, and this along with the Fabry lens in the cooled collimating baffle was constructed from barium fluoride (BaF_2). The physical properties of BaF_2 ⁸ have proved to be superior to those of other materials tried, including KRS-5 and Irtran II.

To permit operation at the high altitude site, a semi-portable telescope was constructed in the CIT Central Shops utilizing a 50.8-cm diameter paraboloid loaned by the Mt. Wilson and Palomar Observatories. A convex secondary and a flat mirror were used to bring the $f/15$ optical beam coincident with the declination axis of the German mounting system. The telescope and instrumentation were installed in a concrete block building located near the Barcroft Laboratory of the White Mountain Research Station near Big Pine, California. The elevation at this site is about 3900 m (12,800 ft).

The optical path followed by the $f/15$ beam is illustrated in Fig. 3. The working component of the photometer was a rotating chopper mounted at a 45° angle to the incoming beam. In order to suppress the unwanted background radiation from the sky as well as that from the optical components within the field of view, the total energy from the background plus object was reflected into the cell during the first half-cycle while the chopper blade was in the closed position. As the chopper rotated into the open position during the next half-cycle, radiation from an adjacent portion of the sky was reflected into the cell by a fixed comparison mirror located at the same 45° angle but slightly below the chopper blade. The ac output of the cell represents background plus object minus background, or to a good approximation, that due to the object alone. For planetary objects the spacing between the measuring beam and the reference beam is about 5 min of arc. Good correlation between the two beams was usually observed under this condition; although, the null signal from a uniform sky nevertheless displayed some low-frequency drift. A spacing which provided 20 min of arc separation between the two beams was necessary for lunar observations, which resulted in some increase in background noise.

Detector and Cooling Dewar

Although several detectors of the doped germanium type meet the minimum sensitivity requirements for an $8\text{--}14 \mu$ infrared telescope system, mercury-doped germanium (Ge-Hg) was selected over the more common varieties for two important reasons. First, the long wavelength cutoff for Ge-Hg coincides closely with the useful upper limit of the $8\text{--}14 \mu$ atmospheric window, thus eliminating the need for special cutoff filters to

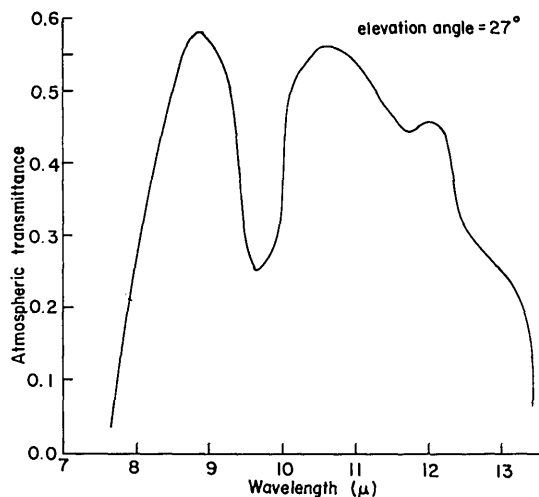


Fig. 2. The spectral transmission at Palomar after Sinton and Strong.⁵

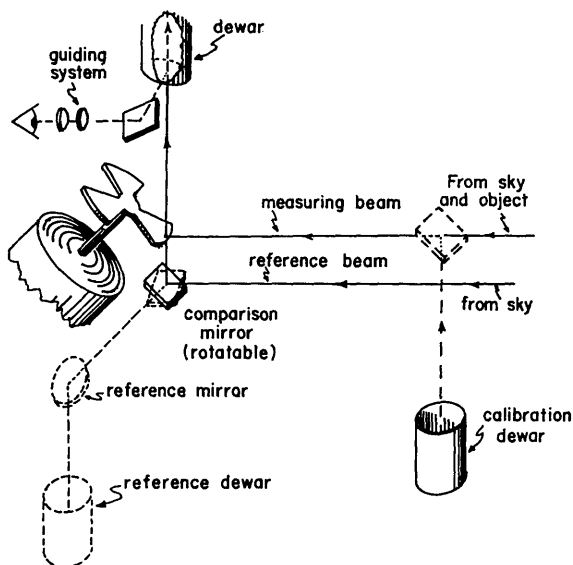


Fig. 3. The optical paths followed by the measuring and reference beams through the photometer.

block the strong atmospheric emission beyond $14\ \mu$. Secondly, the wider ionization energy gap of Ge-Hg makes it possible to achieve adequate cell resistance and sensitivity using liquid hydrogen as the coolant rather than liquid helium, a distinct advantage in the type of field operation for which the system was designed.

Two $2 \times 2\ \text{mm}$ Ge-Hg crystals, manufactured by Texas Instruments, Inc., and supplied to us by the Naval Ordnance Test Station, China Lake, California, were mounted in two modified Linde LNI-28 dewars as shown in Fig. 4. The dewars are designed for use with either liquid helium or hydrogen using liquid nitrogen shielding. Modifications included a 12.7-cm window extension to provide space for a special baffle system which limited the detector field of view to about $f/15$. As indicated in Fig. 5, the converging $f/15$ beam from the telescope was brought to a focus at the entrance aperture located on the front surface of the dewar window. This room temperature aperture was an elliptically shaped hole sandblasted in a microscope slide cover glass and mounted at a 15° angle to the optical axis, providing effectively a 1-mm diam circular aperture. The surface surrounding the aperture was aluminized to reflect the star or planet image into a guiding eyepiece system when the image did not fall completely within the aperture.

After leaving the focal plane, the diverging optical beam passed first through the 0.5-mm thick BaF_2 window, then through a series of cooled baffles in thermal contact with the liquid hydrogen heat sink. These cooled baffles effectively removed most of the stray radiation outside the $f/15$ cone. An interference type optical filter with a cut-on at $8.2\ \mu$ was also located within the cooled radiation shield. Finally, a 9-mm diam BaF_2 Fabry lens was used to refocus the divergent

beam on the sensitive area of the detector, forming a real image of the primary mirror.

Operated in this manner the detector had an angular field of view of about 10^{-3} steradians with the enclosing radiation shield cooled to liquid hydrogen temperature. Under these conditions the resistance of the Ge-Hg crystals was about $1\ \text{M}\Omega$ at sea level. However, as the ambient pressure on the liquid hydrogen was reduced by moving to higher elevations, the resistance of the detectors increased markedly, reaching $8.0\ \text{M}\Omega$ at the 3900-m site on White Mountain. Although cell resistance was remarkably constant at a given altitude, it was necessary to determine cell operating parameters such as bias current at the observing site.

Another property of these detectors that had not been expected was a noticeable increase in response at very low frequencies. The normal photoconductive time constant of these detectors is of the order of $1\ \mu\text{sec}$. However, at modulation frequencies below 200 cps it was observed that additional response with a very long time constant began to appear. This is possibly explained as an added bolometer effect due to actual temperature changes in the crystal produced by absorbed radiation, an effect which is especially apparent under the nearly complete radiation shielding used here. The effect is even more pronounced because operation with liquid hydrogen places the Ge-Hg detector on the knee of the resistance versus temperature curve.

Although the dewar has been designed for a holding time of several hours with liquid helium, there are several advantages in being able to use liquid hydrogen as the cooling medium. The holding time with liquid hydrogen averaged about 80 hr in the LNI-28 dewar,

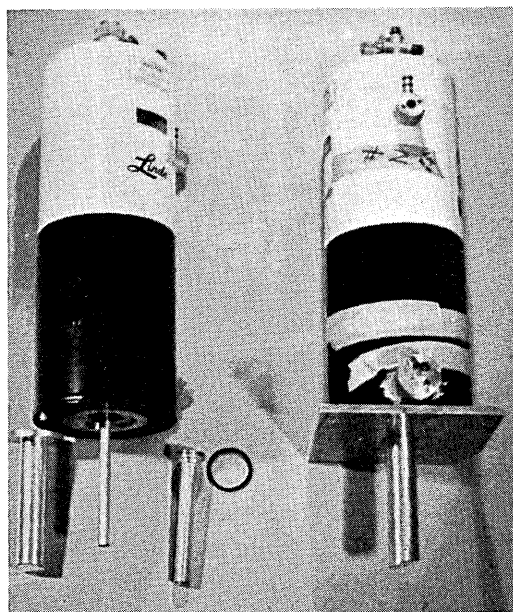


Fig. 4. Photograph of the modified Linde LNI-28 dewars showing the window extension and radiation shield.

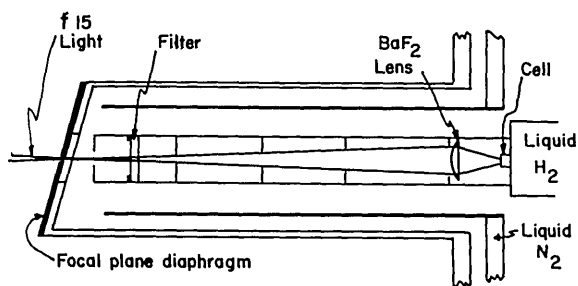


Fig. 5. Diagram of the aperture and cooled radiation shield.

completely eliminating the need for refilling during an all-night observation run. In addition, the comparative ease with which liquid hydrogen can be handled and stored, coupled with relatively low cost, are added benefits. A further increase in Ge-Hg detector sensitivity might, in principle, be realized by using liquid helium, but the very high resistance obtained (hundreds of megohms) under such complete radiation shielding leads to serious difficulties in the electronic circuitry. A noise equivalent power approaching 2×10^{-12} W has been achieved in practice. The corresponding detectivity D^* (273°K, 180, 1) approaches 5×10^{10} cm(cps) $^{1/2}$ /W for the 8.5–13.5 μ wavelength interval.

Electronics

As indicated in Fig. 6, the Ge-Hg detector was connected in series with a load resistor of several megohms to a battery bias supply. The chopped radiation incident on the cell causes a variation in resistance which in turn produces a small ac voltage at the modulation frequency. This signal was amplified by a low-noise amplified (Infrared Industries Model 600 tuneable microvoltmeter) and fed into a special autocorrelation detector network. A small lamp and silicon photocell mounted near the chopper were used to produce a square-wave reference signal phase locked to the chopper and, hence, to the ac signal from the infrared detector. This square-wave signal was used to switch a four transistor synchronous detection network of the type described by Smith *et al.*⁹ The overall bandwidth of the system was controlled by a simple lowpass filter at the output. A recorder (Sargent Model MR) with a mechanical integration device attached to the pen allowed the signal to be recorded at a bandwidth of about 1 cps with the possibility of deriving narrower bandwidth from the chart by direct integration.

Calibration

For calibration purposes a set of auxillary mirrors was incorporated into the photometer. At the beginning, and at various times during an observation period, a calibration procedure was followed which consisted of measuring the signal produced by alternately viewing two blackbodies at different temperatures. These

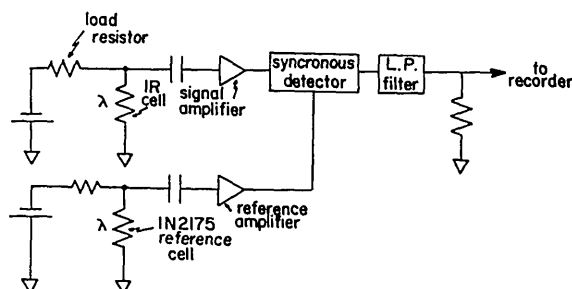


Fig. 6. Schematic diagram of the electronic circuitry.

blackbodies were blackened-metal cavities in thermal contact with liquids of known temperature (usually ice water and liquid nitrogen) contained in a standard glass dewars.

To view one of the blackbodies, a mirror was inserted into the measuring beam path as shown in Fig. 3. The second source was viewed in the reference beam by rotating the comparison mirror 180° and using a second mirror to reflect the optical path down into the blackbody. Since two reflecting mirrors were used in each path, the signal generated represented the difference in radiant power emitted by the two blackbody surfaces. This was computed directly from the Planck radiation law assuming unit emissivity of the calibration sources.

Operation

The system described has performed successfully over a period of several months at a high altitude observing site on White Mountain. Normal procedure for planetary and stellar observation has been to balance the reference and measuring beams closely with the telescope trained on the sky near the object. Once a noise level trace has been established, the telescope was moved on the object and maintained there by occasional small adjustments in the slow motion guidance. The operator's view through the guiding eyepiece of the focal plane image as reflected by the aluminized aperture gave absolute evidence that the radiation from the object was falling on the detector.

It was observed that fluctuations in the emitted sky radiation collected by the two beams was usually the limiting factor in length of time a faint source could be observed. Such fluctuations are probably caused by slight differences in emission of the air masses viewed by the two beams as evidenced by slow random drifts of the recorder pen. When both beams are trained on the sky on a few clear nights with moderate winds, the turbulence in the atmosphere was a severe problem and occasionally made it necessary to suspend operation. Usually conditions were best in the early morning hours from midnight to sunrise. The daylight hours at the White Mountain site are often characterized by rapid cloud formation as the relatively moist air from the Owens Valley is forced over the summit by the prevailing westerly winds. Under these conditions

and even when the clouds were not actually visible, the sky noise was extremely high. A combination of sky fluctuations, optical surface temperature variations, and variations in the cell responsivity due to changes in pressure on the liquid hydrogen, combined to limit the minimum detectable temperature of this system under good conditions to about 105°K for an extended object outside the atmosphere.

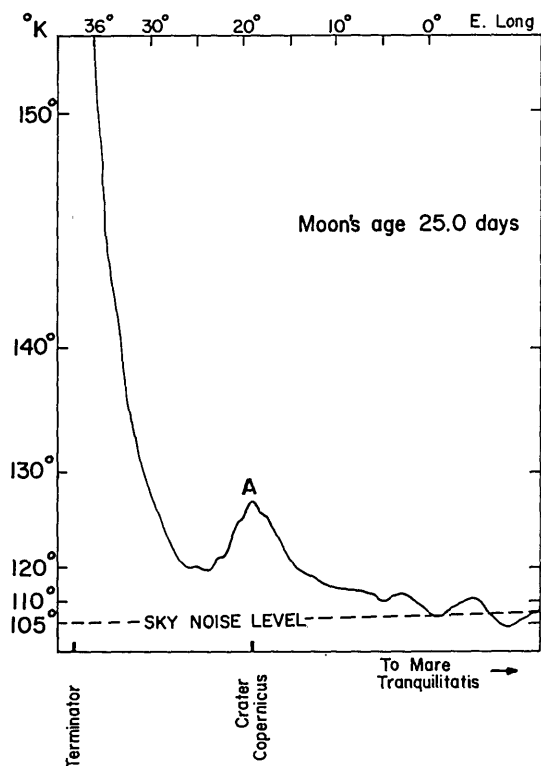


Fig. 7. Recorded signal obtained as the telescope was traversed across the dark portion of the moon at 1119 UT 25 August 1962. The traverse began at the terminator in the vicinity of crater Kepler and extended to near Mare Tranquillitatus. The warm area shown at A is associated with the crater Copernicus.

In the case of the moon, where a position reference is required for data reduction, a photograph of that object superposed on a reference reticule pattern was obtained through a low-power telescope attached to the main telescope tube.

Performance

Although a full discussion of the measurements obtained with this system will be presented in a later paper, a brief summary of the results will illustrate the nature of the data. Figure 7 shows the recorded output as the telescope was traversed across the moon at 1119 UT, 25 August 1962. The observed peak at "A" indicates an area definitely warmer than its surroundings and is possibly due to the presence of bare rock surfaces in the vicinity of Copernicus. The geographic resolution of the system is about equivalent to a circular area 50-km diam at the surface of the moon. Several of these relatively warm areas have been recorded and further study is being conducted.

An average of several measurements of Jupiter has yielded an effective temperature of 128°K at a signal-to-noise ratio of about 10:1 for a one-second observation time. A measurement of the star α Orionis (Betelgeuse) yielded a signal-to-noise ratio of 3:1 for the same observation time.

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